# Development of Diagnostic Techniques to Identify Bypassed Gas Reserves and Badly Damaged Productive Zones in Gas Stripper Wells in the Rocky Mountain Laramide Basins

Final Report

May 15, 2001 to July 15, 2003

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**Stripper Well Consortium**

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## Overview

The northern Rocky Mountain Laramide Basins (RMLB), especially in Wyoming, contain a huge, bypassed, underpressured gas resource that presently is penetrated, severely damaged, or commonly bypassed when operators drill to deeper, traditional overpressured gas assets. Most mud programs used to drill these "basin-center" targets are overcompensated during penetration of the gas-charged underpressured section, which occurs between normally pressured and overpressured rock/fluid systems. This approach results in stripper well gas production from severely damaged, underpressured reservoir rock, or completely bypassed pay zones; explaining in part why Wyoming leads the Nation in the increase of gas stripper wells (1909 gas stripper wells in 1999 and 10,321 gas stripper wells in 2001).

The largest gas fields in Canada (Elmworth, Milk River, Hoadley) and the largest composite domestic Rocky Mountain gas field, the San Juan Basin, are underpressured. The potential for underpressured gas production in Wyoming is huge, but remains bypassed or underdeveloped. To exploit this energy resource, RMLB operators must recognize the magnitude of the undeveloped, underpressured gas resource, and then must treat underpressured gas prospects as priority targets, instead of as incidental targets penetrated during drilling of deeper, traditional overpressured gas resources.

The goal of the work described in this report was to provide the techniques necessary to identify bypassed gas and badly damaged productive zones in RMLB marginal gas wells. This goal was achieved by first examining individual wells to identify the problem, then developing diagnostic tools, and, finally, applying and testing these tools on a regional scale. Use of the technology developed in this project allows operators to predict qualitatively under- and overpressured terrains prior to drilling, thereby allowing them to avoid bypassing gas pay and to minimize drilling and completion damage.

In order to establish the magnitude of the problem of bypassed or damaged pay zones in RMLB marginal wells detected on the scale of a well, one must evaluate the problem on a regional basis. For this regional exercise, the Wind River Basin was chosen because of data availability.

## Well-Specific Investigation

The study area consists of the Wind River and Greater Green River basins (Figure 1), which together contain 5,537 gas wells, of which we have access to complete log suites and production data for 375 wells. From the 375 wells, 45 test wells were chosen for the proposed work, including commercial gas wells, gas stripper wells, and abandoned gas wells. For each of the 45 wells, the following tasks were completed:

- Determination of the thickness of the underpressured zone beneath the pressure surface boundary from sonic and mud logs, and acquisition of DST and RFT data where available.
- Evaluation of complete log suites for each well, with special emphasis on determining the relationships among the velocity inversion surface (i.e., sonic log), mud log, high resistivity, neutron and density porosity (i.e., gas crossover), gamma ray, and caliper logs.
- Compilation of production data patterns and trends for the 45 wells.
- Evaluation of each well type (stripper, abandoned, gas) using the compiled data:
    - Thickness of underpressured zone
    - Distribution of gas-charged sandstones and fractured shale
    - Production characteristics
    - Distribution of the rock-fluid system that has been exposed to overcompensated mud weight (e.g., potential damage zone)
- Integration of the data and determination of the potential for bypassed gas and damaged productive zones in each of these three types of wells and determination of the most

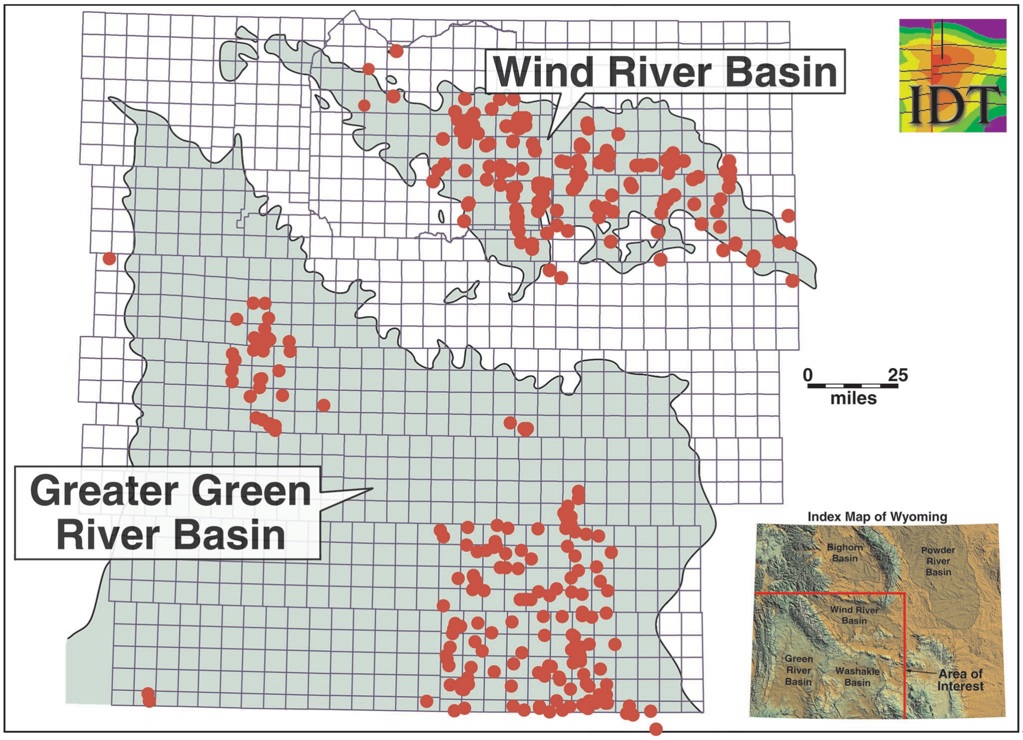


Figure 1. Index map of the study area, the Greater Green River and Wind River basins, WY.

effective, efficient routines for identifying bypassed gas and damaged pay in the gas stripper and/or marginal wells.

*Data Collection*

Wellhead information was assembled and sonic and mud logs digitized for each of the 45 wells (Table 1). Gamma ray, neutron porosity, density porosity, resistivity, and caliper logs were acquired and have been evaluated. Available initial production, production zone, DST, and RFT data also was acquired.

*Determination and Delineation of the Fluid-Flow System*

The fluid-flow systems in the RMLB are known to be compartmentalized, both on a regional and local scale. Regionally, these basins are divided into at least three large compartments; locally, these large compartments are subdivided into several smaller compartments (Figure 2). The boundary between the normally pressured, water-saturated fluid system and the underlying anomalously pressured, gas-charged fluid system is characterized by a significant sonic/seismic velocity inversion, which corresponds to the regional pressure surface boundary. Below this boundary, the velocity can be up to 2000 m/s slower than that predicted by the *ideal* regional velocity/depth gradient. The regional pressure surface boundary is especially important because in the RMLB, a huge portion of the cumulative gas production, including most gas stripper wells, is from reservoirs spatially located below, but within 2000 feet of the boundary (Surdam, 1997; Surdam, 2001a; Surdam, 2001b; Surdam, 2001c; Surdam et al., 1994, 2001).

Sonic logs from 45 wells (Table 1), combined with DST, RFT, and mud data, were used to determine the fluid-flow regime (i.e., the pressure surface boundary and the underpressured zone below this boundary). Anomalous velocity profiles were generated for all 45 wells (Figures 3 through 5). The anomalous velocity was calculated by systematically removing the

Table 1. List of wells used in this project.

**Greater Green River Basin**

| Well Name | API # | Township | Range | Section | Status |
|---|---|---|---|---|---|
| Canyon Creek Unit 32 | 4903722827 | T12N | 101W | 9 | SI |
| Cherokee Ridge Federal 1 | 4903720518 | T12N | R96W | 15 | A |
| New Moon Unit 1 | 4903722317 | T13N | R95W | 13 | SI |
| Federal 3-5 | 4903722029 | T14N | R100W | 5 | A |
| CEPO Lewis 21-18 | 4903724185 | T14N | R95W | 18 | Gas |
| Windmill Draw Unit 1 | 4903721071 | T15N | R94W | 14 | SI |
| Lario Federal 33-14 | 4903724076 | T15N | R94W | 15 | SI |
| Mull Federal 44-18 | 4903724124 | T15N | R94W | 18 | Gas |
| Wester Federal 33-6 | 4903724352 | T15N | R94W | 6 | Gas |
| Mulligan Draw Unit 6 | 4903722912 | T15N | R95W | 25 | Gas |
| Coal Gulch Unit H 1 | 4900720662 | T17N | R93W | 2 | Gas |
| Champlin 256 | 4903720763 | T17N | R96W | 3 | A |
| C. G. Road Unit 26-3 | 4903723919 | T21N | R94W | 26 | Gas |
| Beaver Mesa 1-7 | 4903720416 | T24N | R102W | 7 | A |
| Federal 21-1 | 4903722021 | T24N | R103W | 21 | Gas |
| Freighter Gap Unit 1 | 4903721904 | T24N | R12W | 13 | SI |
| Freighter Gap Unit 2 | 4903721982 | T24N | R12W | 12 | A |
| Federal 1-1 | 4903722261 | T24N | R14W | 1 | A |
| Packsaddle Unit 1 | 4903721425 | T25N | R103W | 24 | A |
| Federal Q 1 | 4903721096 | T25N | R96W | 28 | Gas |
| Musketeer Unit 1 | 4903721966 | T26N | R101W | 8 | A |
| Golden Rod Unit 1 | 4903520601 | T27N | R109W | 30 | A |
| Wardell Federal 1 | 4903520342 | T28N | R108W | 9 | SI |
| Tot Unit 31-22 | 4903521652 | T28N | R109W | 22 | Gas |
| Yellow Point Federal 11-13 | 4903521887 | T28N | R109W | 13 | Gas |
| Stud Horse Butte 13-27 | 4903521359 | T29N | R108W | 27 | Gas |
| Stud Horse Butte 5-26 | 4903521374 | T29N | R108W | 26 | Gas |
| Wagon Wheele 1 | 4903520124 | T30N | R108W | 5 | SI |
| West Pinedale 1 | 4903520348 | T30N | R109W | 33 | SI |

**Wind River Basin**

| | | | | | |
|---|---|---|---|---|---|
| Shoshone Arapahole Tribal 534 | 4901320612 | T1S | R2E | 2 | SI |
| Ocean Lake Tribal | 4901321430 | T2N | R4E | 8 | SI |
| Tribal 24-11 | 4901320748 | T3N | R3E | 11 | A |
| Ocean Lake Tribal 1-15 | 4901321312 | T3N | R3E | 15 | Gas |
| Tribal MR 30-13 | 4901321772 | T4N | R3E | 30 | Gas |
| Tribal Chevron 30-11 | 4901320725 | T4N | R3E | 30 | Gas |
| Tribal Sand Mesa 2 | 4901320800 | T4N | R4E | 24 | Gas |
| Coastal Owl Creek 1 | 4901321077 | T5N | R3E | 26 | SI |
| Ryan Hill Unit 1 | 4902520002 | T32N | R84W | 35 | A |
| HSR Steele 16-31 | 4903521725 | T34N | R109W | 31 | SI |
| Twindale 1 | 4902521344 | T34N | R87W | 15 | Oil |
| Federal USA 17-1 | 4901320961 | T34N | R94W | 17 | Oil |
| Wild Horse Butte 1-16 | 4902522015 | T35N | R88W | 16 | A |
| Nawking Draw Unit 2 | 4901320488 | T35N | R90W | 25 | A |
| Horseshoe Creek Federal 1 | 4901321546 | T35N | R92W | 26 | Si |
| Fuller Reservoir Unit 2 | 4901320565 | T36N | R94W | 25 | SI |

# 2½D Anomalous Velocity Model, Western Wind River Basin

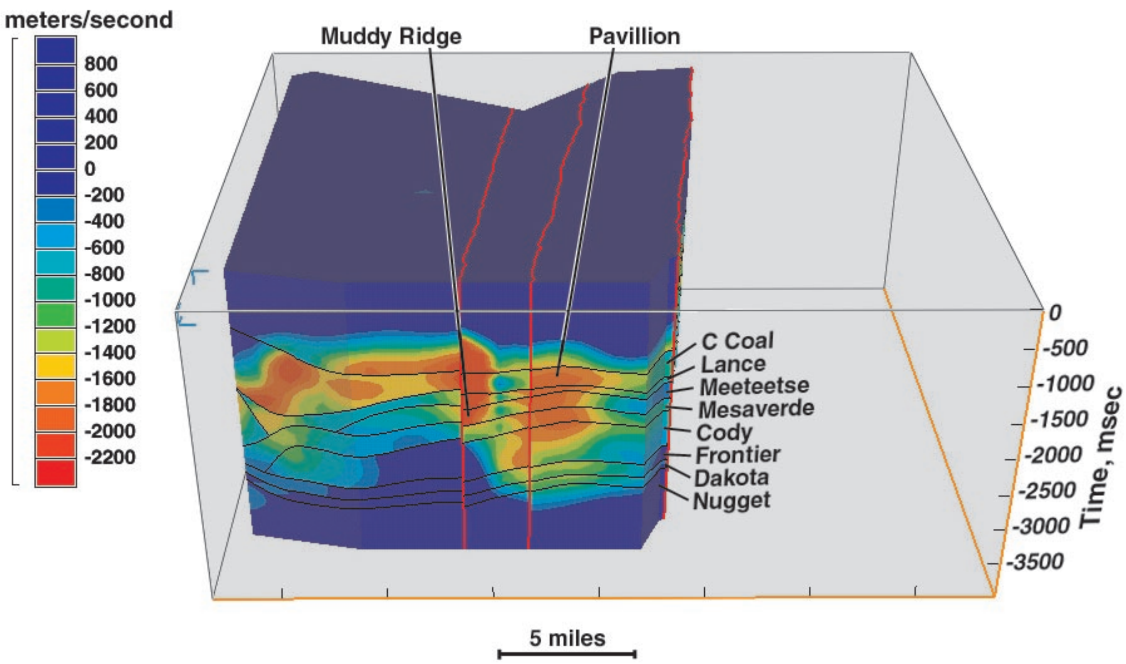


Figure 2. An east-west cross section cut through a 2 ½ D anomalous velocity model showing pressure compartmentalization in the Western Wind River Basin, Wyoming. Red and yellow areas indicate an anomalously pressured and gas-charged rock/fluid system.

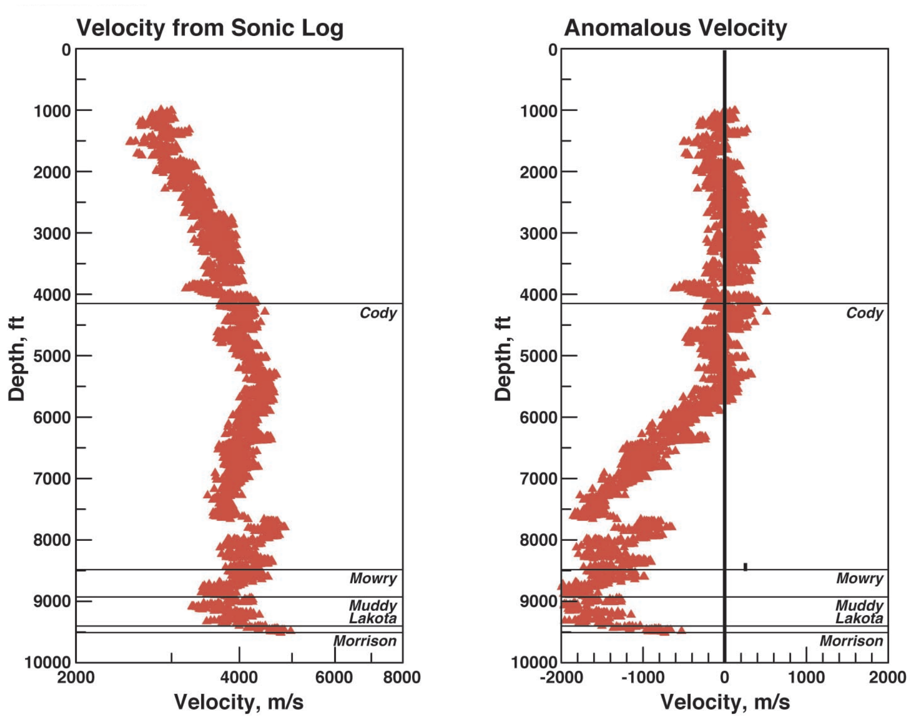


Figure 3. Sonic velocity and anomalous velocity profiles for a well from the western Wind River Basin, WY. The pressure surface boundary is at 5700 ft.

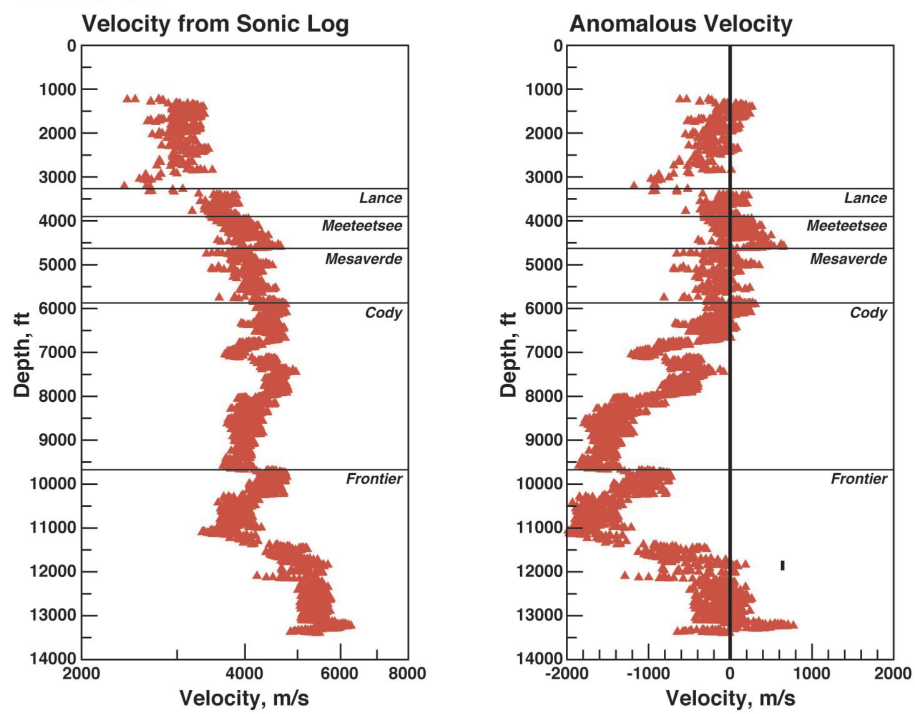


Figure 4. Sonic velocity and anomalous velocity profiles for a gas well from the western Wind River Basin. The pressure surface boundary is at 6600 ft.

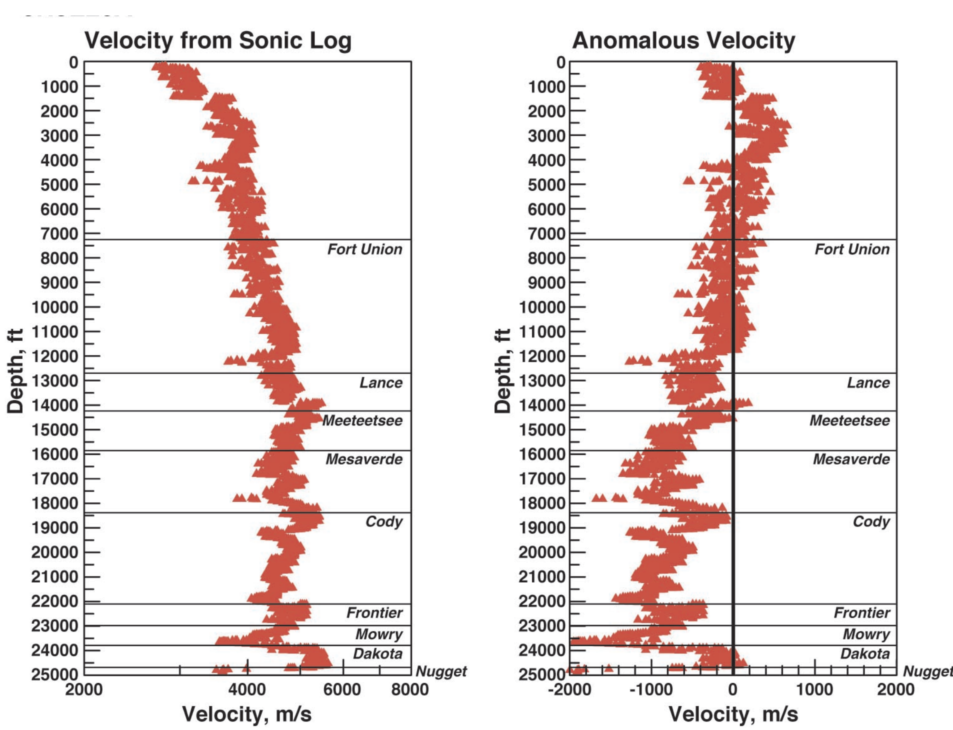


Figure 5. Sonic velocity and anomalous velocity profiles for a well from the northwestern Wind River Basin. The pressure surface boundary is at 11,800 ft.

*ideal* regional velocity-depth gradient from the sonic velocity profiles. Rocks with normal velocity/depth trends (i.e., falling on or near the velocity/depth hydrostatic gradient) are characterized by normal pressure and a water-dominated, single-phase fluid-flow system, whereas rocks with anomalous velocity are characterized by anomalous pressure (overpressure or underpressure) and a multiphase fluid-flow system (Surdam et al., 1997).

These anomalous velocity profiles are used to determine the: (1) pressure surface boundary, (2) interval with anomalous pressure, and (3) gas-charged, anomalously pressured section (Figure 6). The gas-charged, underpressured section can be identified on the anomalous velocity profile by using the pressure data (i.e., DST, RFT, and mud log data) (Figure 7).

*Determination of Badly Damaged Productive Zones*

Because the pressure transition configuration present in the study area was poorly understood or unknown to drillers when many of the RMLB gas stripper wells were drilled (prior to 1990), operators, from experience, assumed they would encounter overpressuring at depth. The drillers' primary concern, with respect to safety and control of the well, was for a transition from normal to overpressure; consequently, they increased mud weights during drilling. However, in the RMLB, underpressuring is often encountered at depth; thus, many of these underpressured zones were drilled with overcompensated mud weights (Figures 6 and 7). In this drilling situation, the potential for bypassing or highly damaging productive zones was *significant* and resulted in wells that produced only a fraction of the available gas.

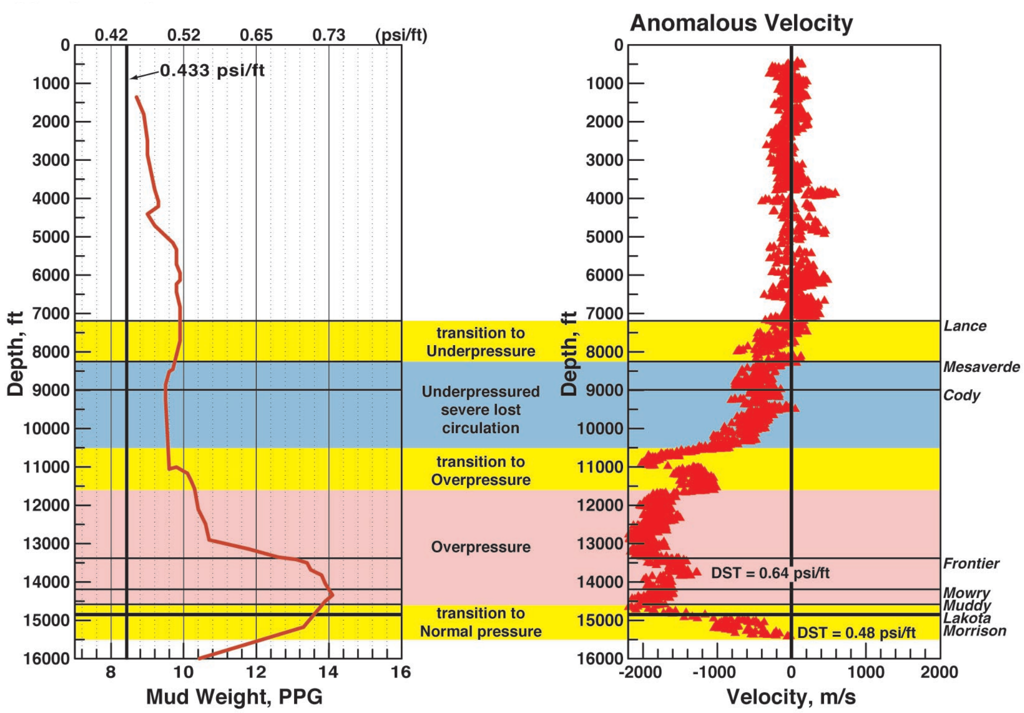


Figure 6. Mud weight profile and anomalous velocity profile for a well from the eastern Wind River Basin. The regional pressure surface boundary is at the top of Lance at 7200 ft depth. The underpressured zone is from 8250 to 10,500 ft depth. The mud weight used to drill the underpressured interval was 9.6 ppg, or significantly overcompensated.

In order to determine where badly damaged productive zones occur in the study area, mud logs were plotted with anomalous velocity profiles. For example, Figures 6 through 10, which include both mud weight profiles and anomalously velocity profiles, show how mud weights were overcompensated in the underpressured stratigraphic section. Figure 6 shows both profiles. Here, the regional pressure surface boundary occurs at the top of Lance at 7200 ft depth, and the underpressured zone occurs in the 8250 to 10,500 ft depth interval. The mud weight used to drill this gas-charged underpressured interval was 9.6 ppg, which was significantly overcompensated. Figure 7 shows both a mud weight profile and anomalous velocity profile; the regional pressure surface boundary occurs at 8000 ft depth in the Fort Union Formation, and the underpressured zone occurs in the 8000 to ~13,500 ft depth interval. A pressure gradient 0.39 psi/ft from DST is measured at the depth 10,000 ft, so the mud weights should have been less than the weight of water (i.e., < 8.4 ppg). The mud weights used to drill this underpressured interval were 8.6 to 9.2 ppg, also overcompensated. In Figure 8, the regional pressure surface boundary is within the Cody Formation at 6300 ft depth, and the anomalously pressured zone occurs within the 6300 to ~10,000 ft depth interval. The mud weights used to drill this anomalously underpressured interval were 8.9 to 9.4 ppg, again overcompensated; there is no indication that the upper potion of this anomalously pressured zone is overpressured, but instead is underpressured. Figure 9 is for a well from the Washakie Basin, Wyoming. The regional pressure surface boundary occurs at 6500 ft depth in the Fort Union Formation, and the anomalously pressured zone occurs from 6500 to DT. The mud weights used to drill this anomalously underpressured interval were 8.9 to 10.3 ppg, again, an overcompensated mud program.

It is clear from these preliminary results that the mud weights used to drill gas-charged underpressured sections were significantly overcompensated (and potentially damaged the zone) and were common in the both Greater Green River and Wind River basins (Figures 8 and 9). In fact, numerous gas-charged intervals were overcompensated with heavy mud. The logic for these conclusions is as follows:

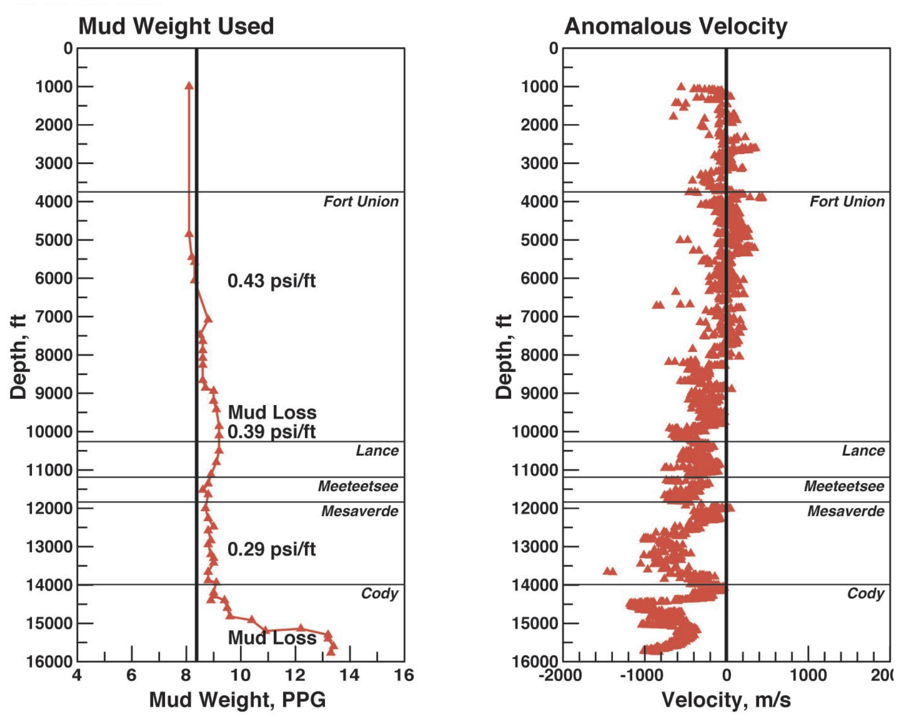


Figure 7. Mud weight profile and anomalous velocity profile for a well from the Wind River Basin. The regional pressure surface boundary occurs in the Fort Union Formation at 8000 ft depth. The underpressured zone is from 8000 to ~13,500 ft depth. A pressure gradient of 0.39 psi/ft from DST is measured at 10,000 ft depth, so mud weights should have been less than the weight of water (i.e., < 8.4 ppg). However, mud weights used to drill this underpressured interval were 8.6 to 9.2 ppg, also significantly overcompensated.

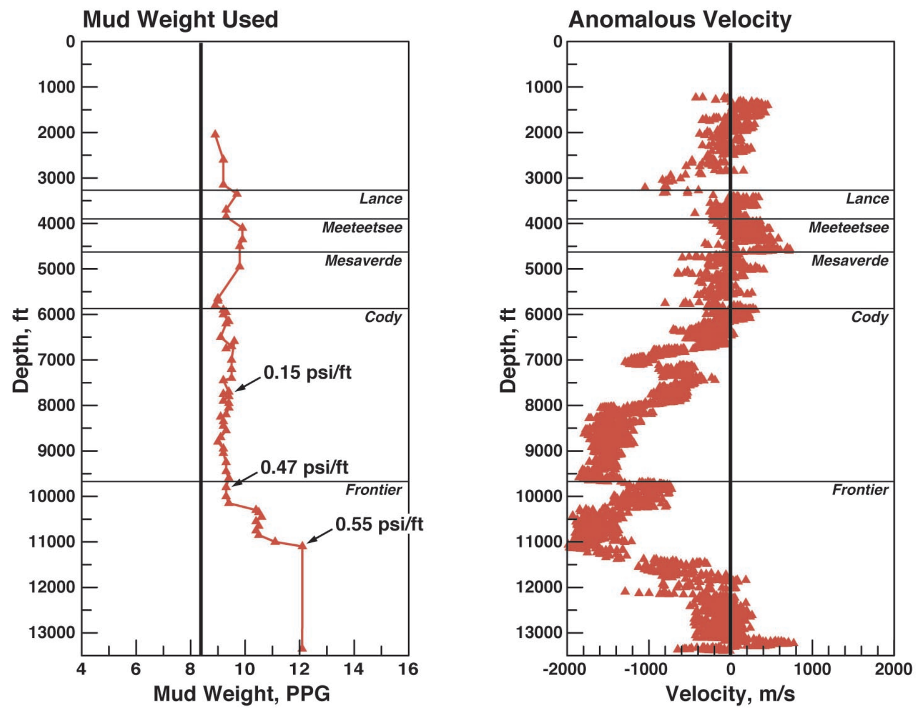


Figure 8. Mud weight and anomalous velocity profiles for a Wind River Basin well. The regional pressure surface boundary is in the Cody Formation at 6300 ft depth. The underpressured zone is probably from 6300 to ~10,000 ft depth. Mud weights used to drill this interval were 8.9 to 9.4 ppg. There is no indication that the upper potion of the anomalously pressured zone is overpressured rather than underpressured. Thus, mud weights used to drill the gas-charged, underpressured section were significantly overcompensated.

1. The rock/fluid systems are gas-charged (i.e., have anomalously slow velocities), so they must be either overpressured or underpressured, as they do not fall on the hydrostatic gradient as a result of the gas charge.
2. If the section being drilled were substantially overpressured, it would have to be drilled with mud weights greater than 8.5-9.0 ppg, otherwise control of the well could be lost.
3. If the section being drilled were underpressured (Figure 7), mud weights of 8.5 to 9.0 ppg would be significantly overcompensated.
4. In the examples shown in Figures 8 and 9, the portion of the section of interest is anomalously slow (i.e., gas-charged) and, thus, anomalously pressured. The mud weights are approximately 9 ppg, yet DSTs suggest underpressuring. If so, the mud weight program utilized in Figures 8 and 9 in the upper portion of the anomalously slow velocity section was grossly overcompensated as this portion of the section was penetrated.

These badly damaged zones still contain a huge gas resource that operators can exploit if they can design effective remediation and recompletion strategies for gas stripper wells and some abandoned wells. Therefore, it is important to design techniques to identify bypassed pay and highly damaged productive zones in RMLB gas stripper wells, because in most of these wells, these zones are characterized by an underpressured rock-fluid system (Figures 6 through 10).

For 45 wells, mud weights, velocity inversion surfaces, anomalous velocity profiles, lithology, resistivity, porosity, pressure tools, gas shows, and production data were evaluated. In every case, for the upper portion of the anomalously slow velocity domain (i.e., gas-charged volume), the mud weights were typically 9 to 10 lb/gal. Thus, if any underpressured rock/fluid systems were present in these wells, they would have been badly damaged during drilling (Figure 10). Figure 1 demonstrates that, in the underpressured portion of the section, there are significant potential sandstones reservoirs. The key question is how significant and widespread are underpressured rock/fluid systems in the Wind River and Greater Green River Basins? If underpressured rock/fluid systems are significant and

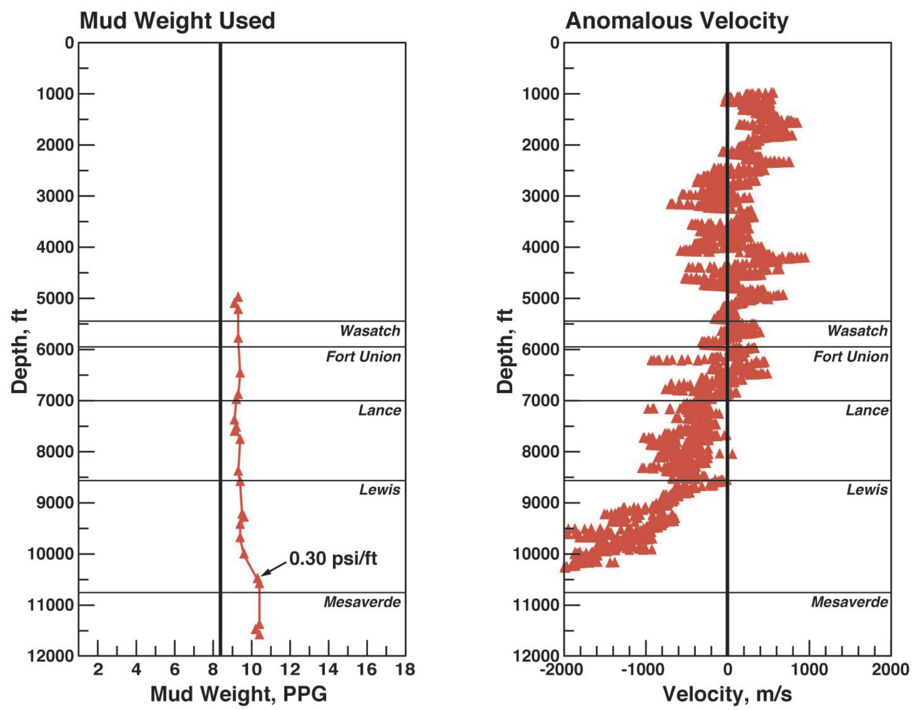


Figure 9. Mud weight profile and anomalous velocity profile for a Washakie Basin, WY well. The regional pressure surface boundary is within the Fort Union Formation at 6500 ft depth. The anomalously pressured zone is from 6500 to DT. Mud weights used to drill this anomalously underpressured interval were 8.9 to 10.3 ppg, again, overcompensated.

widespread, there is huge bypassed gas potential in both existing gas and gas stripper wells.

It is possible to detect significant thicknesses of underpressured, gas-charged sandstone reservoirs in 30 of the 45 wells studied (Table 1); thus, there are large columns of rock/fluid that are underpressured and gas-charged in 30 of the 45 wells studied in the Wind River and Green River basins. Each of the 30 wells in which underpressured, gas-charged reservoirs exist were drilled with 9 to 10 lb/gal mud, or significantly overcompensated mud programs. To determine the magnitude of the resource, the Wind River Basin was chosen for a more detailed regional evaluation.

## Wind River Basin

### *Anomalously Slow Velocity Volumes*

Figures 12 and 13 are the *refined* diagrams for the lower Fort Union and Lance Formations, Wind River Basin, illustrating the anomalously slow velocity domains below the regional velocity inversion surface. The regional velocity inversion surface is equivalent to the pressure surface boundary that separates the normally pressured, water-dominated, rock/fluid systems above from anomalously pressured, capillary-dominated rock fluid systems below. The two anomalously slow velocity volumes shown in Figures 12 and 13 are based on approximately 2500 mi of 2-D seismic lines and nearly 200 sonic velocity logs. Thus, the volumes shown in Figures 12 and 13 were constructed from approximately 132,000 velocity/depth profiles. Surdam et al. (1997) have shown that in the Rocky Mountain Laramide Basins (RMLB), the anomalously slow velocity domains typically are anomalously pressured and gas-charged. From this construction (Figures 12 and 13), the anomalously pressured, gas-charged rock/fluid systems in the lower Fort Union and Lance formations can be detected and delineated. Unfortunately, the velocity evaluation is incapable of distinguishing whether the anomalously slow velocity domains are underpressured or overpressured rock/fluid systems. To make a pressure determination for the volumes shown in Figures 12 and 13, it is essential to integrate pressure data into the analysis.

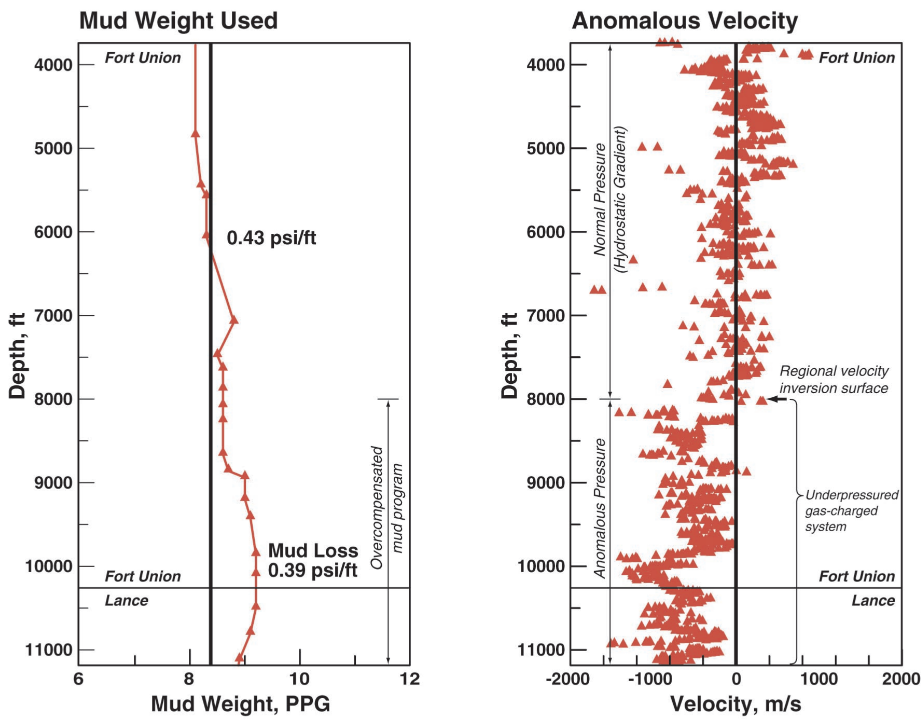


Figure 10. Left: mud-weight profile for a western Wind River Basin well, with available pressure gradients from DSTs. Right: Anomalous velocity profile for the same well. Velocity along the regional normal velocity/depth function falls on the vertical black line; velocities falling left of the vertical black line are anomalously slow and indicate rocks will tend to be gas-charged and anomalously pressured.

*Pressure Data*

Figures 14A,B and 15A,B are the pressure data for the Fort Union and Lance formations in the Wind River Basin, Wyoming. These Fort Union Formation data were originally from 297 wells and 1212 tests, and the Lance Formation data were from 129 wells and 611 tests. The data shown in Figures 14 and 15 were edited according to the following scheme:

1. For the included tests, both the initial shut-in pressure (ISIP) and final shut-in pressure (FSIP) had to be reported or the test was discarded;
2. The ISIP and FSIP values had to agree within 10% or the test was discarded;
3. All pressure data characterized by gradients less than 0.1 psi/ft (i.e., gas gradient) were eliminated; and
4. All pressure data at depths below 12,000 ft were deleted, because below this depth there is a rapid rise n the percentage of overpressured rock/fluid systems.

This data filtering was done to eliminate unreliable measurements and to isolate and focus on the potential for the existence of underpressured rock/fluid systems in the Wind River Basin. The results from the filtered data show that in the Fort Union tests, 72% of the determined pressures were anomalous (i.e., off of the hydrostatic pressure gradient) and of this group, 78% were underpressured. For the Lance Formation, the data show that 75% of the tests resulted in anomalous pressures (i.e., off of the hydrostatic gradient) and of this group, 86% were underpressured. Thus, substantial evidence exists to indicate that significant portions of both the Fort Union and Lance formations — characterized by anomalous velocities (Figures 12 and 13) — in the Wind River Basin, Wyoming are underpressured.

*Regional Pressure Gradient Distribution for the Fort Union and Lance Formations*

In order to translate the information shown in Figures 14 and 15 into a regional context and to integrate the results with the anomalous velocity volumes shown in Figures 12 and 13, regional pressure gradient contour maps were constructed for the Fort Union and Lance for-

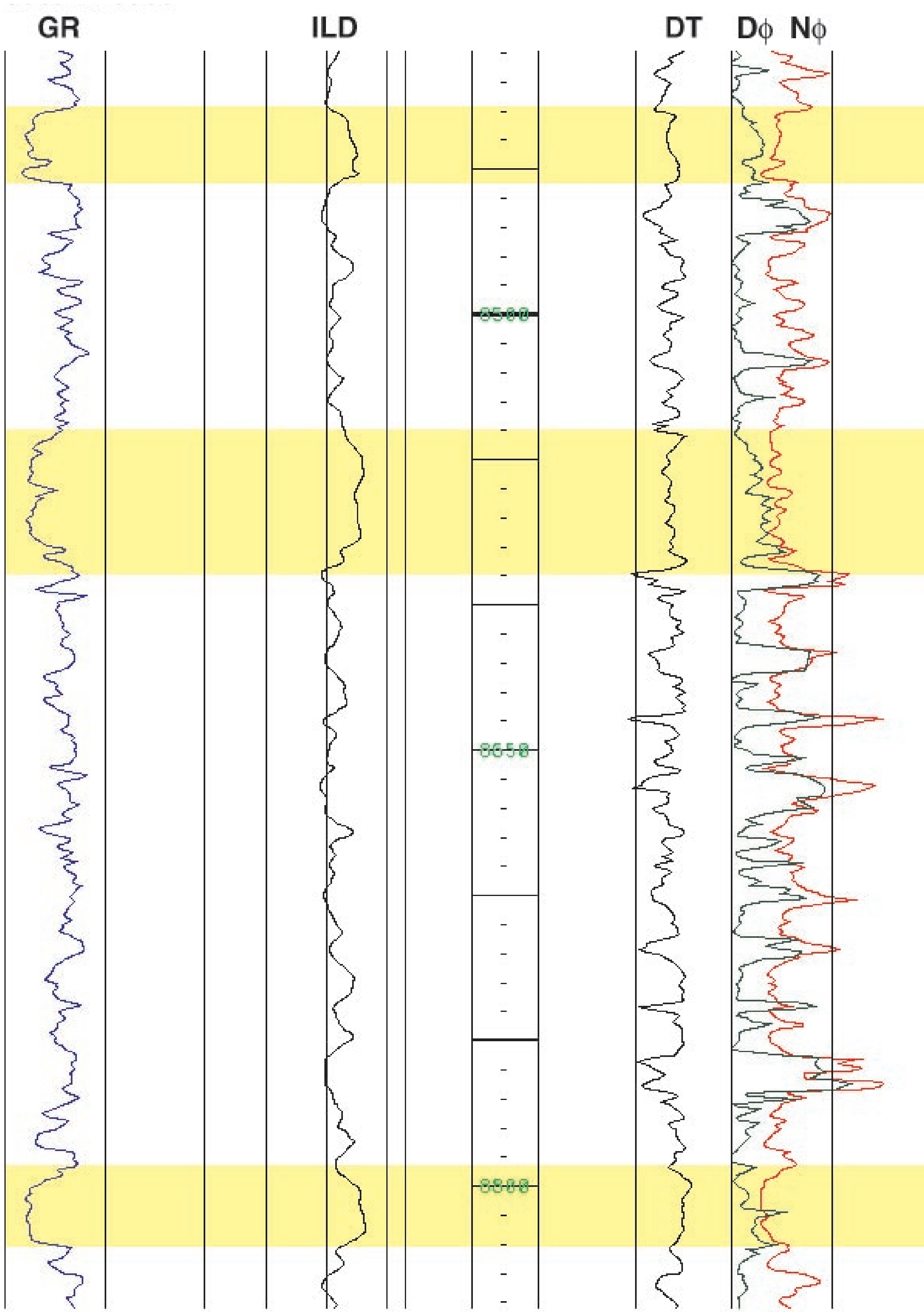


Figure 11. Log suite profiles from a portion (8500-8800 ft) of the well shown in Figure 10. The yellow zones are sandstone intervals that, based on log characteristics, are gas-charged and, from Figure 10, are underpressured.

mations (Figures 16 and 17, respectively). Figures 16 and 17 illustrate that within the Fort Union and Lance formations, there are substantial portions of the rock fluid systems that are underpressured (i.e., pressure gradients <0.4 psi/ft). Most importantly, the underpressured portions of the rock/fluid system are regionally continuous in a lateral sense, and are not broken up into small, discontented pockets (Figures 16 and 17).

*Problems Plaguing the Exploitation of These Underpressured Gas Resources*

Underpressured gas resources in the Wind River Basin and in the other RMLB in Wyoming are being overlooked as significant exploration targets. At best, they are treated as incidental targets encountered while drilling to popular deeper overpressured targets. As a result, the gas-charged, underpressured Fort Union and Lance rock/fluid systems are typically drilled with 9-10 ppg muds (i.e., compensated at pressure gradients of 0.47 to 0.52 psi/ft), leading to the numerous drilling problems plaguing operators while drilling through the underpressured rock/fluid systems. The typical response to these problems is to increase mud weight insuring an increase in the severity of problems such as lost circulation, questionable mud/gas log interpretations, sloughing shales, questionable open hole evaluations, and formation damage.

To our knowledge, there has never been a well drilled in the Wind River Basin solely to test an underpressured target. As a consequence, the huge underpressured gas-charged section in the Wind River Basin at best yields stripper well gas production from severely damaged reservoirs, and at worst the pay zone is completely bypassed. This is one reason why Wyoming leads the Nation in the increase of gas stripper wells (1909 gas stripper wells in 1999

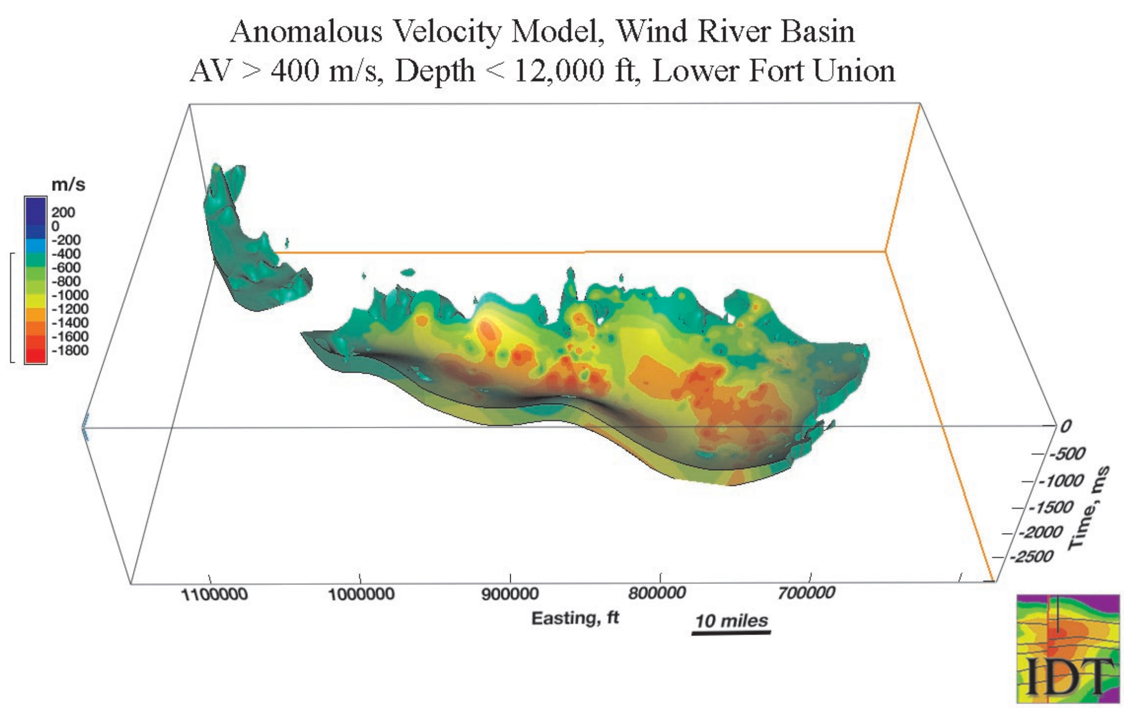


Figure 12. Anomalous velocity model for the Fort Union Formation, Wind River Basin, Wyoming. The normally pressured rock/fluid systems (which plot on the regional hydrostatic gradient) have been stripped off the volume. Only anomalously pressured, gas-charged rock/fluid systems are shown. The anomalous velocity values are derived by removing the ideal regional velocity/depth function from the observed velocity; a minus sign indicates that the value falls below (i.e., slower velocity), or is less than what would be predicted at that point by the ideal regional velocity/depth function. The view in this figure is to the south.

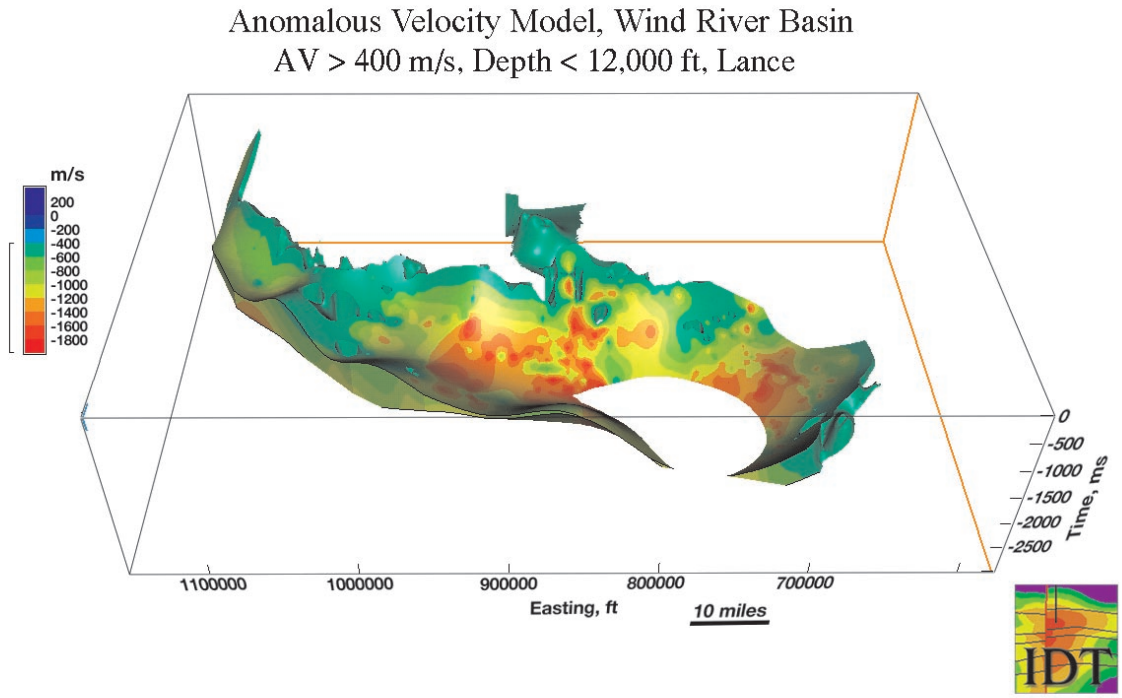


Figure 13. Anomalous velocity model for the Lance Fm., Wind River Basin, WY. Normally pressured rock/fluid systems (which plot on the regional hydrostatic gradient) are stripped off the volume so that only anomalously pressured, gas-charged rock/fluid systems are shown. The anomalous velocity values are derived by removing the ideal regional velocity/depth function from the observed velocity; a minus sign indicates that the value falls below (i.e., slower velocity), or is less than what would be predicted at that point by the ideal regional velocity/depth function. The view is to the south.

and 10,321 gas stripper wells in 2001). In order to exploit this underpressured energy resource in the Wind River Basin of Wyoming and in the other RMLB, operators must recognize the magnitude of this gas resource, and then must treat underpressured gas prospects as priority targets, instead of incidental targets encountered while drilling to traditional deeper overpressured gas resources. Ironically, the largest gas fields in Rocky Mountain basins are underpressured (Elmworth, Milk River, and Hoadley fields in the Alberta Basin and the composite fields in the Sand Juan Basin, New Mexico), yet the possibility and potential of underpressured gas resources in the RMLB of Wyoming is ignored. The work accomplished by the research group at IDT and supported by the DOE Stripper Well Consortium has given operators in the RMLB the diagnostic tools to recognize underpressured, gas-charged rock/fluid systems prior to drilling.

## Diagnostic Techniques

Badly damaged zones can still contain a huge gas resource that operators can exploit if they can design effective remediation and recompletion strategies or select new completion zones for gas stripper wells and some abandoned wells. Therefore, it is important to design techniques to identify bypassed pay and highly damaged productive zones in RMLB gas stripper wells, because in most of these wells, these zones are characterized by an underpressured rock-fluid system.

The following diagnostic steps are suggested in order to determine the presence of underpressured rock/fluid systems in the RMLB:

1. First, the regional normal velocity/depth trend is removed from the observed sonic velocity/depth profile. The results of this operation are two-fold: (1) isolation of anomalously slow sonic velocities and (2) defini-

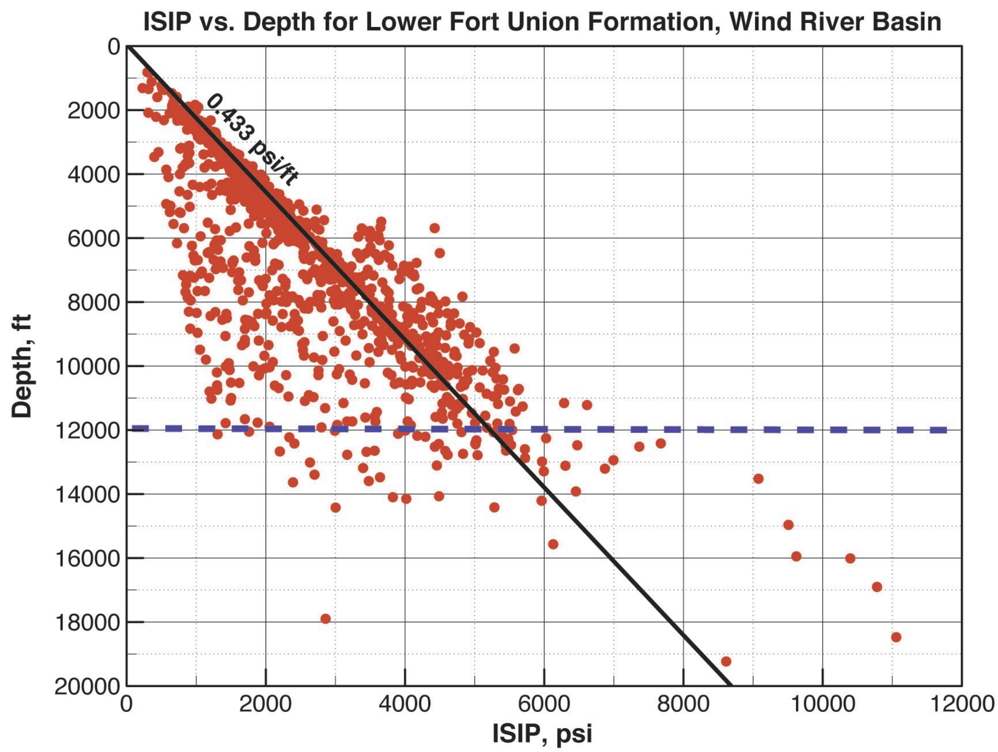


Figure 14A. Plot of the edited (see text) plot of the ISIP vs. depth for the Fort Union Formation, Wind River Basin, Wyoming.

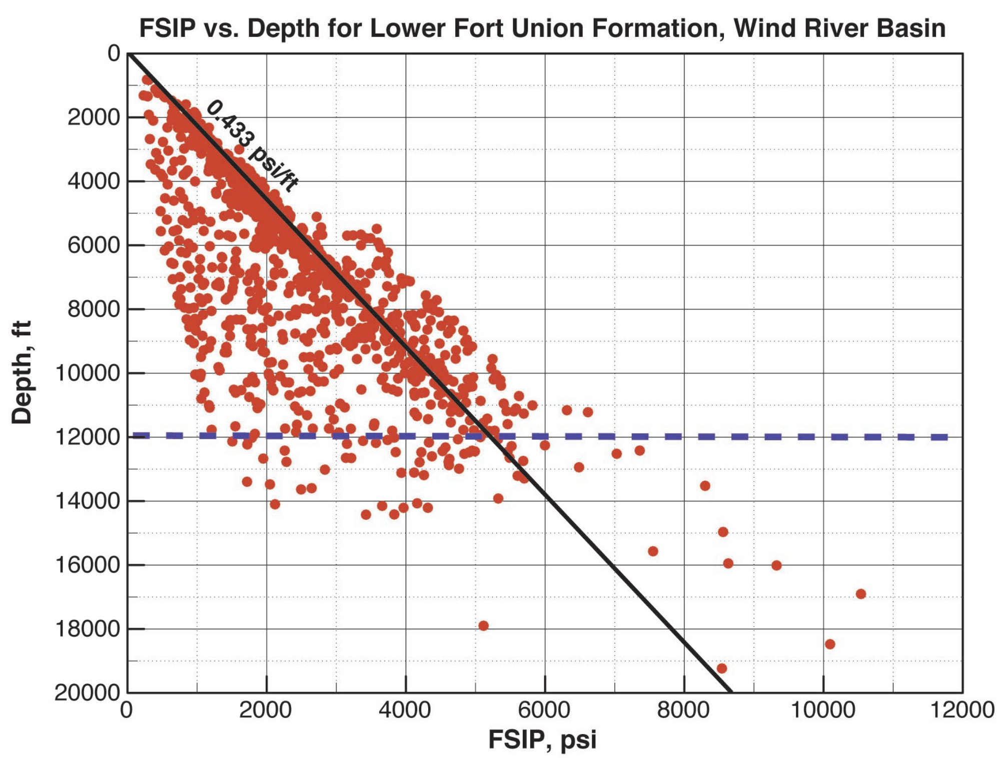


Figure 14B. Plot of the edited (see text) plot of the FSIP vs. depth for the Fort Union Formation, Wind River Basin, Wyoming.

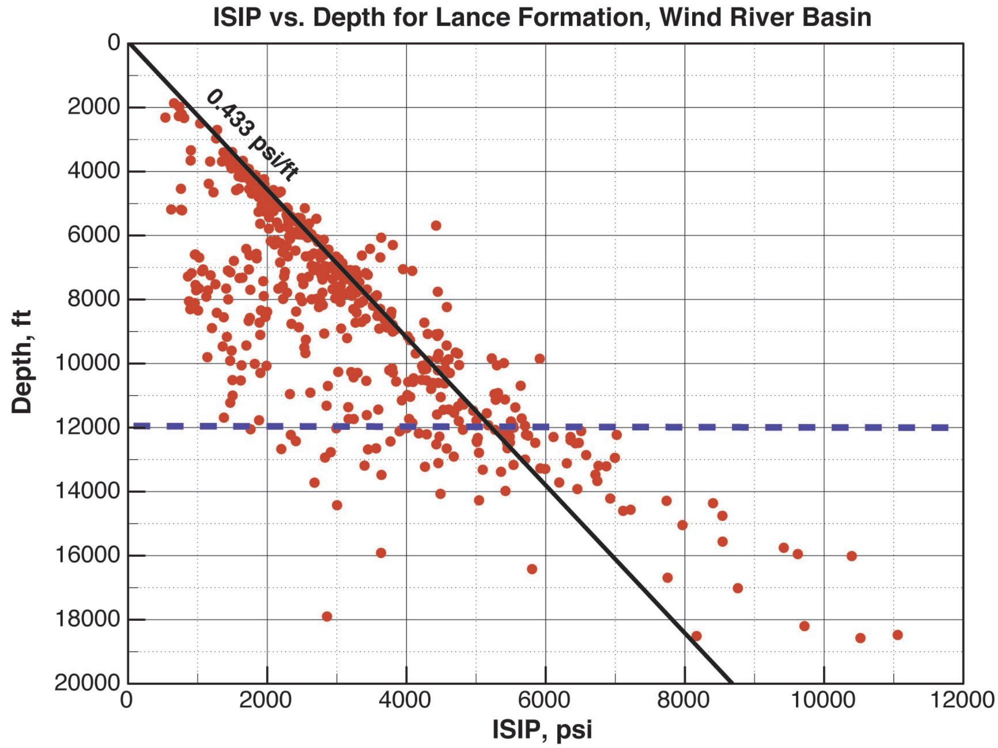


Figure 15A. Plot of the edited (see text) plot of the ISIP vs. depth for the Lance Formation, Wind River Basin, Wyoming.

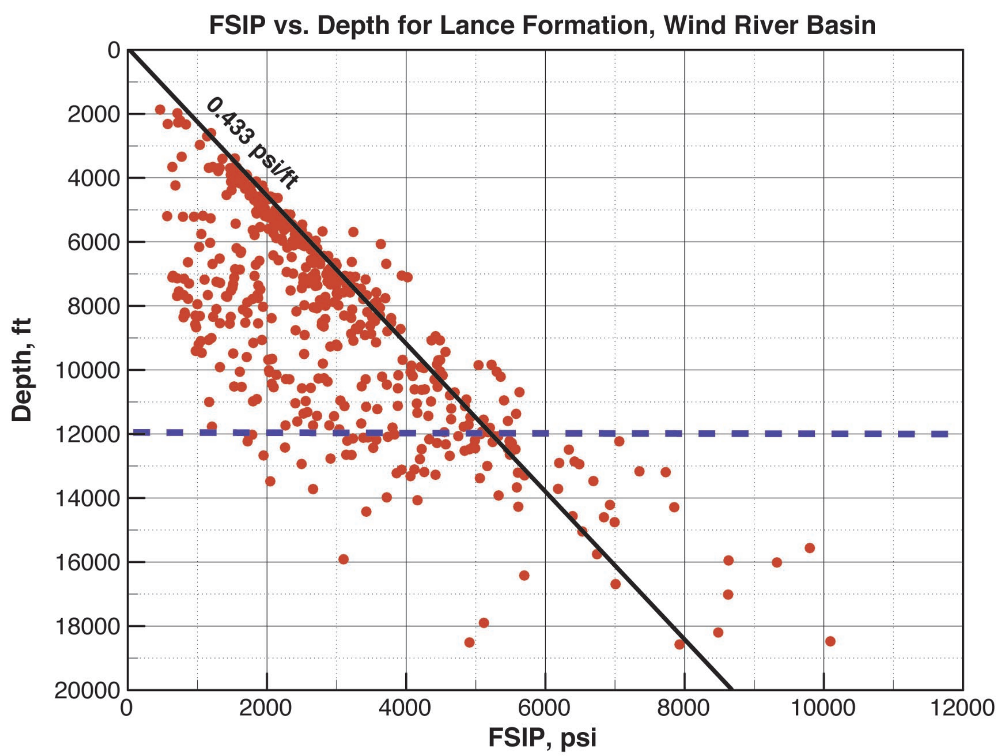


Figure 15B. Plot of the edited (see text) plot of the FSIP vs. depth for the Lance Formation, Wind River Basin, Wyoming.

tion of the regional velocity inversion surface. The isolated anomalously slow velocity domains beneath the regional velocity inversion surface in the RMLB are gas-charged (Surdam, 1997; Surdam, 2001 a,b). Previous work indicates that the regional velocity inversion surface is the boundary between normally pressured rock-fluid systems above and anomalously pressured, gas-charged rock-fluid systems below.

2. Next, the pressure data, derived from drill stem tests and other pressure indicators, are integrated with the anomalous velocity profiles. This integration allows underpressured and overpressured portions of the anomalously slow velocity domain to be delineated.
3. Step three is the evaluation of the distribution of potential reservoir sandstones within the section characterized by anomalously slow velocities and underpressuring. Typically, the relatively thick sandstones within the underpressured, anomalously slow velocity domain are characterized by low gamma ray, high resistivity, high density porosity, and low neutron porosity. These log characteristics are consistent with the interpretation that these sandstones are gas-charged. Where possible, information concerning background gas, gas shows, and gas flows is integrated into the evaluation.

This evaluation scheme could be used to determine the presence or absence of underpressured, gas-charged potential reservoir sandstones. From this sequence of steps, it is possible to detect significant thicknesses of underpressured, gas-charged sandstone reservoirs. In this study, every well that was diagnosed with underpressured, gas-charged sections had been drilled with 9 to 10 lb/gal mud.

This zone of underpressured, gas-charged, rock/fluid has been unrecognized in many of the RMLB because, relative to the San Juan and Alberta basins, the zone tends to be thin in most other basins (Figure 18). In the San Juan and Alberta basins, operators drill from normally pressured sequences, across the regional velocity inversion surface, into a very thick and productive underpressured section (Figure 18; right

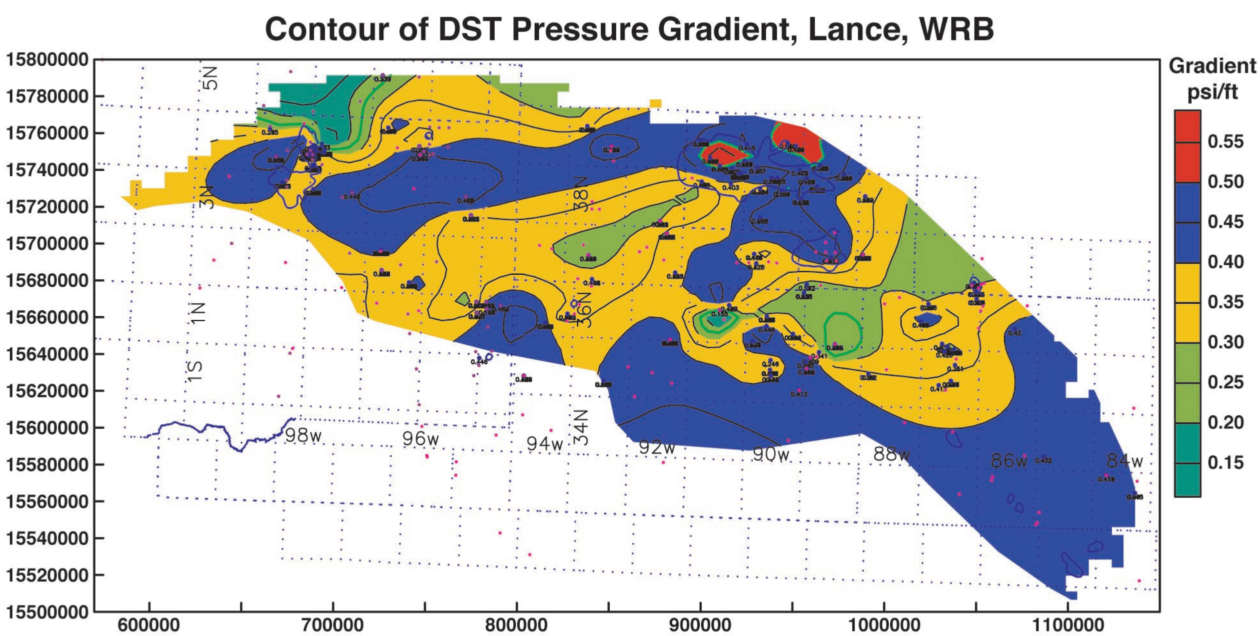


Figure 16. Contour map of the pressure gradients within the Lance Formation, Wind River Basin. Yellow/green areas depict the underpressured rock/fluid systems; red areas indicate overpressured rock/fluid systems; blue areas indicate normally pressured rock/fluid systems. The view in this figure is to the north.

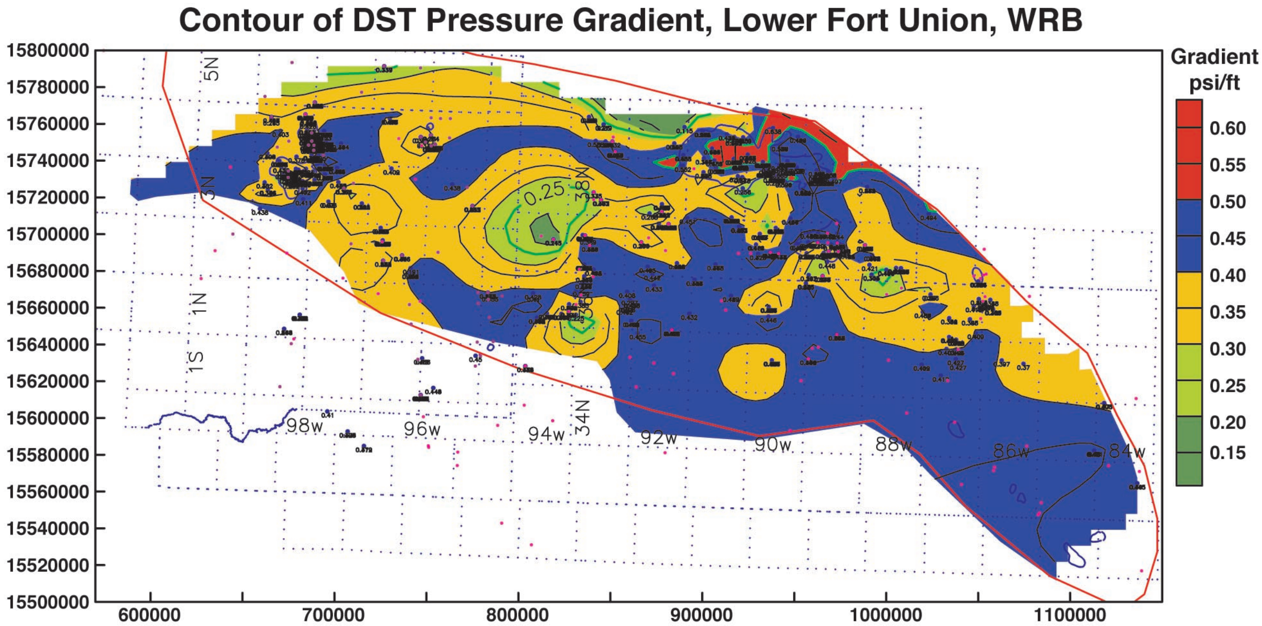


Figure 17. Contour map of the pressure gradients within the Fort Union Formation, Wind River Basin. Yellow/green areas depict the underpressured rock/fluid systems; red areas indicate overpressured rock/fluid systems; blue areas indicate normally pressured rock/fluid systems. The view in this figure is to the north.

side of diagram). In contrast, in the other RMLB, operators drill from normally pressured sections, across the regional velocity inversion surface, into a relatively thin and historically unrecognized underpressured, gas-charged section, *then* into a thick, overpressured productive zone (Figure 18; middle of diagram). Historically, the driller's primary concern has been to prepare for the transition from normal pressure to overpressure. Consequently, most wells, excluding the San Juan and Alberta basins, have been drilled with significantly overcompensated mud programs.

## Conclusions

It is concluded that in the Wind River and Green River basins, significant rock/fluid columns occur that are underpressured and gas-charged. Each of the evaluated wells were drilled with significantly overcompensated mud weight programs. Thus, there is high potential that serious damage occurred during the drilling of the underpressured, gas-charged sandstones, or that gas pay was bypassed. The diagnostic steps outlined in this report will greatly assist operators in predicting the distribution of under-pressured, gas-charged rock/fluid sections.

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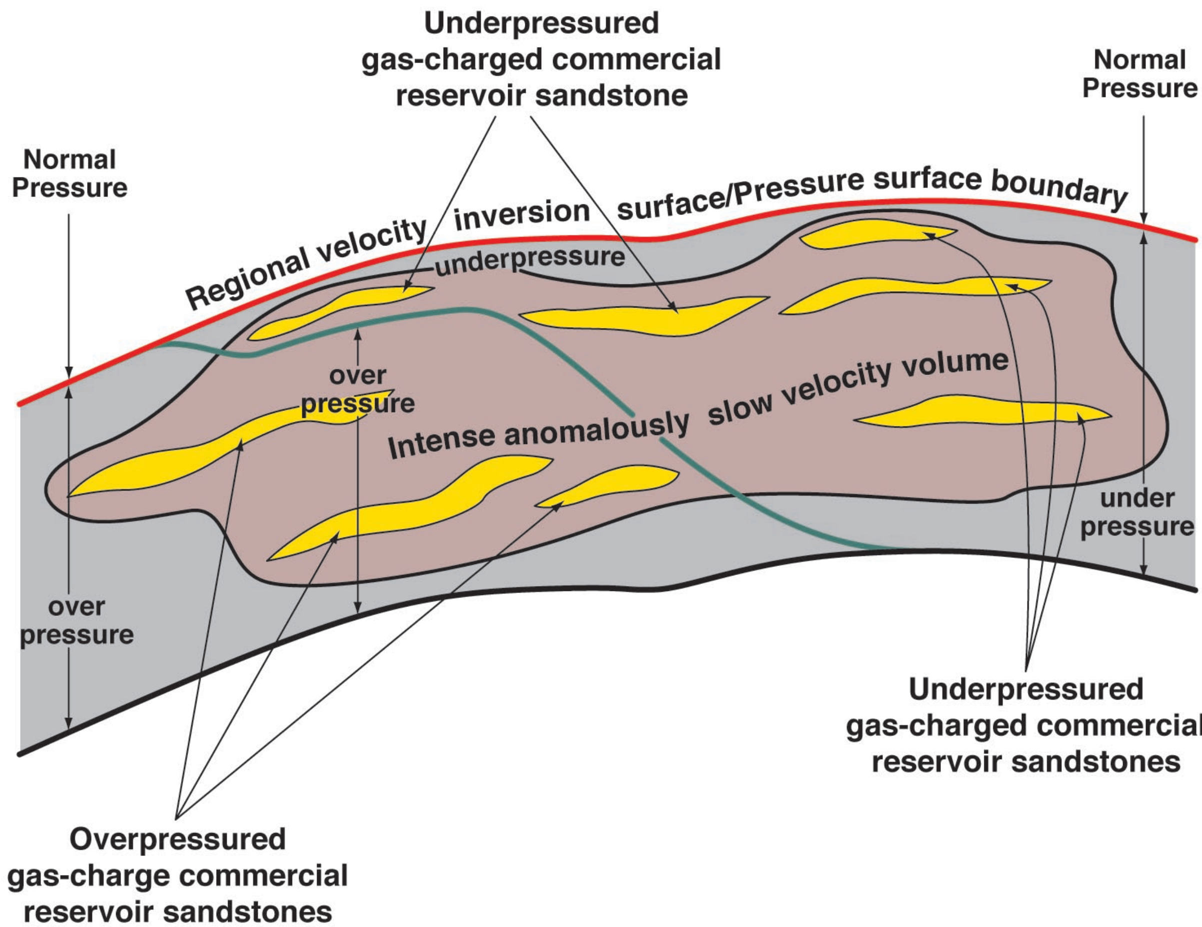


Figure 18. Schematic diagram illustrating the differences in pressure regimes in basins like the San Juan and Alberta basins, as compared to basins like the Wind River and Green River basins. In the San Juan and Alberta basins, the pressure transition is from normal pressure to a thick, underpressured, gas-charged and productive section (right side of diagram). In contrast, in RMLB like the Wind River and Green River basins, the transition is from normal pressure to a relatively thin, underpressured, gas-charged section, underlain by a relatively thick, overpressured, gas-charged and productive section (left side of diagram).

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